Origin and Diffusion of the Herzberg Principle with Especial Reference to Hawaii[1]

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WHEN IT BECAME KNOWN in Hawaii that successful artesian wells had been sunk in many parts of California, various people discussed the question whether artesian water existed in Hawaii. Certain optimists brought a capable well driller from California in 1876, but were emphatically rebuffed when they sought financial help from the government. According to H. M. Whitney (1898), the decision lay with the Finance Minister, who refused money for a test well because he held that all "caverns" below sea level were filled with salt water, and that any rain water reaching the caverns became salt water at once. How wrong he was appeared just three years later when James Campbell, at his own expense, had a good well drilled in Honouliuli.

As more wells were drilled, it was learned that holes near the sea or near the axes of valleys were apt to be failures. We have no evidence as to how well the hydrologic conditions were understood. In 1882 Judge McCully described the successes to that date. Appended to his article is some material by an unnamed writer, who thought correctly that the fresh water was prevented from escaping to the sea by impervious strata, which he called "very compact clay." This, certainly, is a very important factor in the modern explanation of the artesian conditions in Honolulu.

Schuyler and Allardt concluded in 1889 that the Pearl Harbor Springs and the artesian wells drew from the same source of supply, as shown by the fact that water rose in the artesian wells only a little higher than the highest springs. They wrote, "The probabilities are that the island is surrounded by deep thick strata of impervious clay . . . , that these strata lap onto the land to the height the water rises in wells, . . . and that these strata prevent the escape of the waters into the sea beneath them." They seem to be the first to point out the relation between the height of what we now call "cap rock," and the artesian level. A diagrammatic cross section illustrates their views to some degree. Unfortunately their report was a private affair and was not widely circulated, one supposes, so that their understanding of the extensive "basal ground water body," as we now call it, was not utilized by others.

In 1875, Franklin C. Hill told how good water could be gotten by digging shallow wells in sand islands off the Gulf Coasts of Mississippi and western Florida. He explained the presence of fresh water by analogy to an "ash leach," a vessel, such as a barrel, tight enough to hold wood ashes but with small openings at the bottom through which liquids could escape. Hot water poured in on top of the wood ashes leaches out potassium salts, sinks downward and out at the bottom. As more and more water is added it drives the previous lots of water downward with little mixing. Hill draws a parallel with water from rain driving salt water down to some depth

[1] The Herzberg principle holds that in oceanic islands and along shores of larger land masses fresh water floats on and is underlain by sea water because of their differences in density.

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on sand islands making what he called a "lake of fresh water held by the sand in the midst of the sea." He shows that with a porosity of one-third, a 12-foot layer of sand is equivalent to a lake 4 feet deep, and that an acre would hold about one and a quarter million gallons. He seems not to have considered the relative densities of fresh and salt water or of pure water and water holding potassium salts in solution.

In the next decade much progress was made in Europe. In 1888–89, W. Badon Ghyben, a Captain of Engineers in the Netherlands Army, as a result of studies near Amsterdam, found fresh water under the coastal dunes and resting on salt water, and observed that the depth to the salt water increased inland from the shore. He assumed that the specific gravity of North Sea water was 1.0238, from which he calculated that the depth below sea level to salt water was about 42 times the height of fresh water above sea level (1.000/0.0238 = 42.01).

A better exposition of the idea was published by Alexander Herzberg in 1901, based on studies on the island of Norderney. A hole was drilled near the middle of the island to learn about its geologic structure. Cox's translation reads, "It could not be doubted after these observations that the fresh water floated on the subterranean salt water." In another place we read, "The deep position of the sea-water boundary is a function of the height of the ground water table in the dunes above mean tide level in the sea." Herzberg used 1.027 as the specific gravity of North Sea water and from it calculated that the sea water boundary was 37 times as far below sea level as the water table was above sea level. Although Herzberg did not publish until 1901, he seems clearly to have made use of the principle as early as 1889, or even 1886, in his work as a consulting hydrologic engineer.

After Herzberg's publication, there was much discussion of the details of the principle by Dutch, Belgian, French, and German workers.

According to Watson (1956), the early Hawaiians had gotten water from small, shallow wells dug near the shore. Between 1894 and 1900 Maui plantations made thirteen large-scale basal water developments which were gigantic forms of the shallow wells of the early Hawaiians. These were large pits sunk from ground heights of 20 to 50 feet, and large volumes of water were pumped by great steam pumps. These installations had two bad features. For one thing the water was rather saline because the fresh water lens was thin in the absence of a cap rock. Secondly, a very long pipe line was needed to carry the water to the cane fields.

In 1899, Henry Perrine Baldwin and his consulting engineer, Herman F. A. Schussler, believed that fresh water extended far inland under central Maui, as what we now call the "basal ground water body." A shaft (H. C. & S. Co.'s "Kihei," No. 3) was sunk about three miles from the shore from a height of 303 feet. The shaft was 323 feet deep and the water table was 6 feet above sea level. Skimming tunnels were driven close to sea level and a large supply of irrigation water was obtained. This was the first "Maui-type basal water development," and has been followed in Hawaii by more than 50 others of the same general type.

Thus it is clear that in the Hawaiian sugar industry the existence of the great basal ground water body was known, even though it had not been satisfactorily explained.

Waldemar Lindgren spent part of 1901 on Molokai, and wrote (1903):

> In the absence of any impermeable stratum or basins filled by clayey materials, such as, for instance, exist on Oahu, there is nothing to prevent the sea water from entering the rocks freely and assuming a level differing but little from sea level. Below a certain level there is no reason to expect anything but sea water.
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> On the other hand, the rain water also sinks freely through the porous rocks until it meets the sea water. Here, at the permanent water level it is held by the counter pressure of the sea water, and in fact rests like a sheet upon the

same. Between the underlying salt water and the fresh water on top of it there is an intermediate zone of varying width in which the two mingle to form brackish water. The fresh water, always receiving additions from above, is slowly but steadily moving to the only outlet it can find —that is, to springs located along the sea shore, just above or a little below sea level.

The surface of the salt water "is . . . about 160 feet below the surface of the ground [near the south shore]. Inland this level sinks. . . . The permanent surface of fresh water rises inland very slowly, so that a mile or more inland the water in wells may stand only a foot or two above sea level."

Attention is called to Dr. Lindgren's reference to the "counter pressure of sea water," and to his observation that the water table rose inland and that the salt-fresh boundary dropped inland. He was very close to developing the idea of the fresh water lens.

In the following years a number of studies were made by members of the U. S. Geological Survey in states bordering the Atlantic and Gulf Coasts.

Harris in 1904 held that fluctuations of water levels in wells in Louisiana were responses to loading and unloading of impermeable strata over the water-bearing strata by tides and by strong onshore winds. Also, that the fluctuations did not depend on any direct connection between the water of the Gulf and the water in the artesian aquifers.

Pennink in 1904 discussed before the International Engineering Congress in St. Louis some of the features of the relationship between fresh and salt water under coasts and islands, based on his work in the Netherlands. Unfortunately the title of the paper (1905) did not reveal this topic, so that it did not come to the attention of geologists. It is not nearly as forthright a presentation of the Herzberg principle as one would wish.

Veatch and others (1906), in a big report on the ground waters of Long Island, N. Y., made no reference to any possible relationship between fresh and salt water. Twelve north-south profiles of the island and its water table have as their bases the line 20 feet below sea level. Curiously these profiles have the pattern for the saturated zone extend out under both the north and south shores, as if fresh water extended under the waters of the bays at the south and those of Long Island Sound on the north. It would seem, therefore, that they gave no consideration to the effect of salt water.

Veatch in 1906, in a smaller paper, wrote that the water level under Long Island coincided with sea level at the shores and became higher inland, but said nothing about any underlying salt water.

Taylor, writing in 1907 of the salinity of some wells in the Texas Coastal Plain, offered no explanation of the salinity.

We now come back to Hawaii again, for in 1908 W. D. Alexander discussed the ideas ascribed to McCully and wrote that McCully (really some unnamed person) held that "it seems evident that the great central stratum of water-bearing rock must be completely surrounded by impervious strata from the surrounding ocean. Were it not so, the water it contains would escape into the sea instead of standing at forty-two feet above it." Alexander agreed with most of these ideas, but not entirely, for he wrote, "On the whole the theory . . . seems . . . to be the most probable one, although it may not be necessary to assume that the 'water-bearing rock must be completely separated by impervious strata from the ocean,' in view of the slowness with which water percolates through rock and gravel, and also of the pressure of the sea water." Unfortunately Alexander did not develop the germ of the idea further, perhaps because not more than 23 well logs could have been available to him then.

It remained for Andrews, in 1909, to make a tremendous advance in the understanding of the artesian system at Honolulu. Like McCully's ghost writer and Alexander, he thought the barrier of "clay" played an important role, but he developed the all-important part played by the balance between salt and fresh water. He wrote, "The water-bearing stratum is the lava of the volcanic dome as it was finally completed by the upbuilding volcanic forces. The water-bearing lava rock is covered with a layer of clay, the product of decomposition of lava, which in turn, is covered with a stratum of coral rock, formed as a fringing reef, above which strata of coral and volcanic material may alternate. The depth below sea level to which the retaining clay stratum would need to extend in order that fresh water in wells should be raised forty-two feet above sea level by the hydrostatic pressure of sea water of density 1.026, is 1614 feet, which is but little deeper than the depths at which clay was found in the deeper wells." (The 1.026 specific gravity for sea water would give a ratio of 38.5 between the depth to sea water and the height of fresh water: 1.000/0.026 = 38.46.)

"An arrangement of coral and clay strata such as here presented fully accounts for the phenomenon of flowing wells on an island of volcanic origin. The lava of the volcanic dome is somewhat porous, penetrated by cracks, and open enough to permit the movement of water; the clay stratum overlying the lava prevents the escape of water upward; the remaining coral and clay strata simply add an overlying mass, and the elevation of the uppermost coral layer above sea level, lined as it is by clay, raises the surface of the underground water accumulations until they escape as springs over the coral brim, or rise above sea level in artesian wells to the height of escape."

Thus it appears clear that Andrews, who had no knowledge of the work done in Europe on coastal ground waters, entirely independently worked out what we now call the "Herzberg Principle." On Dec. 24, 1955, I called on Professor Andrews and we discussed the matter at some length. Apropos of statements sometimes made that Andrews got his ideas from the Alexanders (plural), he told me that Arthur C. Alexander merely transmitted his father's idea that sea water exerted a pressure. Working out mathematically the ratio of the depth to salt water to the height of the water table, as a function of the relative densities of the two liquids was entirely Andrews' idea. Thus Professor Andrews seems clearly to be the first American to give a mathematical expression of the ratio.

Andrews' remarkable insight into the phenomena is also shown by his correctly explaining the so-called "clay," which acts as the restraining member, as the impermeable residual matter due to very advanced weathering in place of the upper or outer parts of the body of lavas. Others had thought that the clay originated as some sort of marine sediment at a time when the sea reached higher on the island. It is hard to think that clay, in water, would remain in place on steep submarine slopes.

It is most unfortunate that Andrews' paper was never printed, for in its typescript form it gained only moderate circulation.

In 1908 Gregory and Ellis described fluctuations of water levels in wells near the Connecticut shore, but did not refer to the density of sea water. They reported one well in Norwalk that had fresh water to a depth of 50 or 60 feet in sand, but only salt water at lower levels. Plugging of the bottom of the well shut off the salt water successfully.

Clapp, also in 1909, reported on conditions in southern Maine, where salt water had been found under fresh water in a good many wells near the shore, but he made no mention of the density of sea water. A typical well in Islesboro, "obtained good water at 181 feet from the surface, but drilling continued, and at 220 feet salt water was encountered. The well was filled with Portland cement to a depth of about 200 feet from the top, the sea water being thus shut off, and the water was reported of good quality in 1906."

Hitchcock, in 1910, in an address to a Special Conservation Meeting held in Iolani Palace, told of the lava rock aquifer and the cap rock of the artesian system. He made some use of Alexander's idea of the pressure of sea water, but made no reference to Andrews' thorough and invaluable development of that idea. This omission by Hitchcock may be taken to illustrate the unfortunately limited circulation of Andrews' paper.

We next go back to Long Island, where Spear in 1912 applied the Herzberg principle, I think for the first time in any American ground water study. He mentions some of the studies made in Europe, and gives a diagrammatic cross section of the lens under a simple island. He shows the derivation of the "40 to 1" ratio where the specific gravity of sea water is 1.025, and also other ratios for other densities of sea water. A diagrammatic cross section of Long Island is given, in which the base of the fresh water lens is truncated by a smooth basement of impermeable rock instead of making the full downward curve. The principle was used by Spear in forecasting the behavior of wells in certain localities.

Unfortunately for geologists, Spear's work was published in an engineering report for the New York Board of Water Supply, which few geologists would be apt to read.

In 1912 the first edition of Keilhack's "Lehrbuch der Grundwasser- und Quellenkunde" was published. It was followed in 1917 by an enlarged and revised edition, pages 162 to 165 of which give an excellent presentation of the work of Badon Ghyben and Herzberg, and others. One cross section shows the conditions in an ideal, symmetrical, homogeneous, permeable, and rainy oceanic island. The University of Hawaii Library received a copy of the second edition as early as 1921, but it has been little used.

Matson and Sanford in 1913 came close to the idea of a lens of fresh water under Florida. Florida, of course, differs greatly from Hawaii in its rock types, structure, shifts relative to sea level, and its hydrology.

One earlier geologist had thought that the fact of finding fresh water in marine limestones to a depth of a thousand feet implied a former uplift of Florida by a thousand feet, but Matson and Sanford pointed out that the uplift need not have been more than enough to give a small hydrostatic pressure. Thus, they had come close to the Herzberg principle, as is also shown by the following quotations.

> The rocks of Florida are all sedimentary and for the most part were deposited beneath the ocean. Such deposits are called marine and originally included sea water, which may be called water of deposition. This included sea water may be gradually displaced by descending rain water—the rate of change depending on the freedom of drainage. Where the rocks are porous and the land high the water of deposition is soon removed, but a low altitude combined with dense rocks gives a very slow rate of escape. The process of removal may extend to some distance below sea level provided porous materials emerge on the bottom of the ocean. The exact depth will be controlled by the relative weights of the columns of fresh water beneath the land and the salt water at the point of emergence.
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> The greater height of the column of fresh water is partly offset by the increase of weight of the sea water caused by its high mineral content and by the friction of the water in the rocks. There must inevitably be a level where the opposing forces counterbalance each other and the underground water becomes nearly static. Below this level the water of deposition is scarcely disturbed.

This was certainly an approach toward the Herzberg principle.

A well at Sumterville, far from the shore, found no salt water though it reached a total depth of nearly 2,000 feet.

Another quotation from Matson and Sanford makes an approach to the idea of a lenticular body of fresh water, and is as follows:

"In passing from the interior of the State toward the coast the depth to salt water diminishes until in many places it may be encountered within less than 500 feet of the surface, though the depth to the strong brines is usually somewhat greater." This passage suggests the downward curve of the lower side of an ideal lens, but does not mention the corresponding upward curve of the water table or top of the lens.

In 1916 Palmer (1920) thought that the gneiss of Long Neck Point, in Darien, Connecticut, had important joints striking about north and south, parallel to the length of the peninsula, and dipping steeply westward. Wells drilled on the west side of the peninsula got fresh water, but those on the east side got only salt water, which was presumably led into them from the Sound by the westward dipping joints.

In the fall of 1919, Palmer (1919) studied the ground waters of Peaks Island in the harbor of Portland, Maine. The island of 800 acres has a discontinuous mantle of glacial till over schists, whose joints are the main source of ground water. The seven drilled wells on the island extended 3, 105, 110, 110, 146, 166 and 276 feet, respectively, below sea level. The chloride contents of the waters of only five were determined and ranged from 17 to 21 parts per million of water. A slight approach to the Herzberg principle is indicated by the following passage, "The zone of active circulation on Peaks Island is probably entirely above sea level except where it is stimulated by the draft of deep wells. There is probably a more or less conical body of fresh water underlying the island, the point of the cone downwards. The limit of this cone is determined by a balance between fresh water originating on the island and the salt water trying to work under the island." From a 1956 point of view it would have been better to have referred to a "conical region in which the joints contain fresh water," and still better to have used "dome" or "bowl" instead of "cone."

A typescript report by Palmer in 1921 for the Bernice P. Bishop Estate dealt with Maunalua, Oahu. This considered the restraining effect of cap rock where it is present, but made no reference to the density of sea water.

In 1919 the field work of Brown, on the relation of sea water to ground water along coasts, led to two papers that are important landmarks in our story. In a first, smaller paper Brown (1922) introduced to American geologists the work of Badon Ghyben and especially that of Herzberg. Besides giving the formulas and their derivation he reproduces Herzberg's cross section of Norderney and also gives diagrammatic sections of the conditions under an ideal, permeable island and along a permeable coast. There is also reproduced a cross section from a Dutch paper by Pennink of a dune ridge on the Holland coast with isochlors outlining the somewhat lenticular body of fresh ground water.

In the fall of 1955 I wrote Dr. Brown asking how he came across the writings of the European workers. His reply was, "As I recall, I deliberately instituted a search of literature in the Library of Congress on Holland's water problems, on the hunch that that should provide illuminating data, due to the coastal dune belt. This led me on to Badon Ghyben. Somewhere later . . . I ran across a reference to Herzberg."

In 1923, Meinzer's *The Occurrence of Ground Water in the United States* was published. This makes no reference to the Herzberg principle. In one place it points out that, where ground water is found in joints, there is more danger of salt invasion if joints dip landward than if they dip seaward. In another place, apropos of the water-bearing Tertiary strata of the Coastal Plains, we read, "Their water is generally good in the areas of outcrop and for some distance down the dip but is likely to become salty where the formations pass to considerable depths in the direction of the sea."

About 1924, Dr. H. L. Lyon (1925) used the ratio of 1.000 to 1.024 for the densities of normal Honolulu artesian water and sea water, in estimating the reduction of our original supply of fresh underground water. This is in the first part of a typescript, the last part of which was published on Jan. 1, 1925, along with the paper referred to next below.

Carson, McCombs and Rothwell (1925) made a report on the artesian wells of Honolulu, and used Dr. Lyon's density ratio. They estimated that the fall in head to 1925 implied that over 50 per cent of the amount of water originally stored underground had been removed. Though they did not use the term, either they or Dr. Lyon seem to have been the first to hit on the idea of "bottom storage."

A report on the ground waters of the island of Lanai by Palmer (1924) includes a diagrammatic cross section of the water table in an ideal, symmetrical, homogeneous, permeable, and rainy island, showing the upward curve, but it does not have the corresponding downward curve of the base of the fresh water body. Apparently Brown's first paper had been forgotten. Wentworth (1925), in his larger report on Lanai, seems to have been misled by Palmer's erroneous, incomplete cross section.

Another great landmark was Brown's larger paper, published in 1925 though also based on his 1919 field work and subsequent office and library work. It adds little for the present purpose, but it surely had a different and more extensive readership than did the earlier, shorter paper. It has formed the basis for subsequent work on ground waters in Hawaii and many other regions. It includes an annotated bibliography of relevant papers.

One important effect of it may be found published in the abstract of Palmer's paper presented May 19, 1926, before the Hawaiian Academy of Science, namely the use of the "U-tube" analogy for illustrating the balance between salt and fresh water.

A fuller paper resulted from the preceding, and was published in October 1926. So far as appears, it presents the first deductive explanation of the artesian conditions at Honolulu, by the use of three progressively more complex cross sections of ideal, oceanic islands. The first is a symmetrical, homogeneous, permeable, but rainless island, in which sea water fills all the voids below sea level. The second adds an effective amount of rain that eventually supplies fresh water to a lens floating on denser sea water. In discussing this cross section the algebraic derivation of the Herzberg ratio, 40 : 1, is given. The third cross section adds an impermeable coastal capping that thickens the edge of the fresh-water lens so as to cause artesian conditions. Combined in this are the three essential factors: (1) the permeable lava rock aquifer; (2) the impermeable coastal plain cap rock; and (3) the Herzberg principle.

On Sept. 10, 1926, Palmer transmitted to the Honolulu Sewer and Water Commission his report on the Honolulu artesian system (1927). The ideas of the paper discussed just above were included and somewhat expanded. This report made several contributions. One was the explanation of the differences in the heads of the several isopiestic areas as a result of their being partly separated by deep valley fills that acted as inverted, underground dams. Another idea, thought to have been new then, was that of ascribing the gradation downward from fresh through brackish to salt water in the "contact zone" to mixing as a result of rise and fall of the contact zone in response to falling and rising artesian heads. With falling head, the contact zone would rise bringing saltier water where fresher water had been; and with rising head, the contact zone would drop and bring fresher water where saltier water had been.

There was also the first, though inadequate, attempt to study the rate of change in the "transition zone," as we now prefer to call the "contact zone." Studies of the reduction of salinity in two wells by plugging parts of the bottoms, gave changes per foot of plug of 1.75 parts and of 25 parts of chloride per million parts of water. The slow rate of change in the first well was thought to be due to greater fluctuations of the depth to the transition zone as a result of greater fluctuations of the artesian head, with more mixing as a result.

From 1926 on there have been many applications of the Herzberg principle, not only at various places in the Hawaiian Islands, but also on many Pacific islands, especially during World War II. There has also been application of the principle, with certain necessary modifications, to the stratified sedimentary rocks of the Atlantic and Gulf Coastal Plains, and to the limestones of Florida, as well as to the glacial deposits of Long Island.

In Hawaii, Dr. Chester K. Wentworth, when he was with the Honolulu Board of Water Supply, made important studies of the specific gravity of sea water in connection with the local value of the Herzberg ratio, of bottom storage, of the growth of the transition zone; and of modifications of the Herzberg principle by taking a dynamic instead of the original static view. Mr. L. T. Bryson, Chemist of the Board of Water Supply, has studied, among other things, base exchange in Honolulu ground waters and the nature of the transition zone. Mr. Doak C. Cox, Geologist for the Hawaiian Sugar Planters' Association, has made great progress in studies of the transition zone, of the effects of ocean tides on ground water levels, and of the dynamic *vs.* static view of the Herzberg principle.

I am indebted to Mr. Doak C. Cox, Mr. Leslie J. Watson, and Mr. Erik Palmer for critical reading of the draft of this paper and for their valuable comments.

EPILOGUE

Some years ago we spoke of just the "Herzberg Principle." Then, when it was realized that Badon Ghyben published first, we spoke of the "Ghyben-Herzberg Principle." Next it was learned that the Hollander's family name was double, viz., Badon Ghyben, so it was felt that we should say the "Badon Ghyben-Herzberg Principle." I now propose that we return to the simple form of "Herzberg Principle," with its various parallels, such as "Herzberg Lens." I believe this is justified, although Badon Ghyben published first, because Herzberg (1) had the idea first and used it, and (2) gave a far better presentation of the idea.

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